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This report discusses the implications to Defense planners of the relationships among the reliability, availability, and spares investment goals of the Army's XM-1 program. The analysis presented demonstrates a method for estimating these relationships based on data available early in the life of a weapon system. The study also examines the effects on availability and spares costs of the extent to which opportunities exist for cannibalization in wartime scenarios.

SPARES COSTS AND AVAILABILITY FOR THE XM-1: A METHODOLOGICAL DEMONSTRATION

January 1980

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Prepared pursuant to Department of Defense Contract MDA903-77-C-0370 (Task ML908).

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PREFACE

This report presents the results of an analysis of the costs of spares support in peacetime and wartime for the Army's XM-1 tank system and the sensitivity of those costs to reliability and, in time of war, opportunities for cannibalization.

This analysis was undertaken by LMI at the request of the Director of Acquisition and Support Planning, Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs, and Logistics). Its purpose was to develop tradeoffs through sensitivity analyses that may be useful in understanding program management options.

ACKNOWLEDGMENTS

We are indebted to our colleagues, Mr. Michael J. Konvalinka, for construction of the data bases used in this analysis, and Mr. William B. Fisher and Mr. Robert S. Greenberg for their many helpful suggestions. We also wish to acknowledge the participation in the analysis of Mr. Michael McGrath and Mr. Martin Meth of the Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs and Logistics).

EXECUTIVE SUMMARY

This analysis examined the relationships among initial spares cost, utilization, reliability, and availability factors in the Army's XM-1 program. Its purpose was to assess the effects on support cost of demonstrated and projected hardware reliability levels and to demonstrate an analytic method for estimating those relationships using a spares optimization model.

Despite the many simplifying assumptions and the paucity of data in the analysis, there were important observations made that are pertinent to the XM-1 program and to future work. Those observations are:

1. The set of long-lead-time, repairable items probably constitutes the most sound basis for estimating the relationships among the critical factors of interest early in a weapon system's life because those items tend to have in common the characteristics of high cost, high removal rate, and mission criticality. They also enjoy the earliest attention with respect to logistics planning; therefore, estimates of their characteristics tend to be refined earlier than those of other items.

2. Although, in general, any conclusions about wartime operations require thorough analyses, it may be possible to establish bounds on system availability in wartime scenarios through application of a simplified spares optimization model with assumptions of no cannibalization and unconstrained cannibalization.

3. Anticipated wartime rates of utilization of the XM-1 are dramatically higher than peacetime rates. Given this condition, we believe that a comprehensive analysis of war reserve stockage requirements should be undertaken using spares optimization techniques. Such an analysis could yield

substantial benefits to the XM-1 program in enhancing its sustainability during wartime.

A concept of fundamental importance emerges from this and previous analyses in support of DSARC decisions. That concept relates to the use of spares optimization models in weapon system support planning. In this analysis, the use of such a model enabled us to estimate the relationships among spares investment cost, reliability, and availability. We believe that this analysis serves as an illustration of an approach to weapon system support planning that not only explicates tradeoffs and program management alternatives, but also illustrates how to perform such analyses early in the life of a weapon system when planners face a serious paucity of data. Clearly, some method is required to estimate as accurately as possible, given data constraints, the relationships among the important weapon system characteristics examined in this analysis. It seems prudent in a planning context to use a spares optimization model because it will find the least-cost mix of spares for any specified level of weapon system availability, thus providing a conservative estimate of the relationships among important program and logistics factors being considered.

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PROCEDURES

The objective of this study of the XM-1 tank system was to estimate the relationships among reliability, availability, and spares investment by applying availability optimization models to the peacetime and wartime phases of XM-1 operations. The availability models were used because they take explicit account of a number of factors, including: (1) weapon-system availability, (2) the relative worth of spares (i.e., trade-offs among different spares), and (3) the multi-echelon structure of the logistics system.

The first half of this study focused on peacetime operations; the second half on wartime operations. Three XM-1 data bases, each representing a different level of reliability, were used throughout the analysis. These data bases corresponded to reliability levels of 145 mean miles between failures (MMBF), 240 MMBF, and 320 MMBF. The 145-MMBF data base reflected component reliabilities achieved (after spurious failures were eliminated and demonstrated fixes were accounted for) during Operational Test II (OT II); the 240-MMBF data base reflected the reliabilities estimated by the Program Manager (PM) if all planned engineering changes were effective; the 320-MMBF data base reflected the component reliabilities associated with the Army's reliability objectives for the early 1980s. The data bases and their sources are described in the last section of this chapter.

The peacetime half of the study began with an analysis of the sensitivity of availability and spares cost to changes in reliability. The relevant availability in this study was supply availability, i.e., the probability that

a randomly selected tank is not waiting for a part to be repaired or be shipped to it. The relevant cost was the spares cost in FY79 dollars required to maintain the peacetime availability of approximately 2000 tanks (roughly the number of XM-1s slated to be in the European theater in the mid-1980s).

The analyses in this task were performed with the aid of a spares optimization model called DRAMA.[1] DRAMA requires system- and component-level input data. The system-level data are: (1) the repair time and order-and-shipping time at each echelon (Organizational, Direct Support, General Support, and Depot), (2) the number of tanks being spared, (3) the required availability level, and (4) the number of brigades. The required component-level data are: (1) the distribution of repair and condemnation activity among echelons, (2) the number of component applications per tank, (3) each spare's unit cost, and (4) the expected number of removals per hundred-thousand-miles. DRAMA's output consists of a cost-versus-availability curve and a list of the optimal stockage quantities of each component. The lists from DRAMA's peacetime runs were used in our wartime studies to represent the spares status of XM-1 brigades at the start of hostilities.

The second task in our peacetime study was to estimate the additional spares cost of war reserves. This involved the development of a cost-estimating equation and its application to each of the XM-1 data bases.

The wartime half of the study involved the application of two analytical models, one that assumed unconstrained cannibalization (called CANNIB) and one that assumed no cannibalization (called NOCAN), to each of the XM-1 data bases. These models traced the declining availability of a typical XM-1 brigade over the course of a 30-day war. The two models were identical in all respects but one. CANNIB assumed that parts shortages were consolidated in as

[1]DRAMA is an acronym for Diagnostic Reliability, Availability, and Modularity Analyzer.

few tanks as possible, thus generating upper bounds on availability; NOCAN assumed no cannibalization, thus generating lower bounds on availability. By applying both models, we made explicit the impact of the opportunity for cannibalization on wartime availability.

PEACETIME ASSUMPTIONS

The following assumptions were made in applying DRAMA to the XM-1's peacetime scenario.

1. There are 17 active brigades in Europe, each consisting of 121 XM-1 tanks.
2. All tanks obtain their spares from one of the 17 brigade-controlled inventories called Authorized Stockage Lists (ASLs).
3. All ASLs are resupplied from a single higher echelon. The resupply time from this echelon is the weighted average of the depot and the general support (GS) resupply times.
4. There is no lateral resupply, i.e., brigades do not share spares with one another.
5. There is no cannibalization.
6. There are no tanks in float.

The first assumption is based on a total FY 1984 population in Europe of 3883 tanks (including both M-60 and XM-1 tanks) in 32 brigades resulting in an average of 121 tanks per brigade. The assumption was made that 17 of the brigades would be active, the same number used by the Army in their Combat Evaluation Model, and would be equipped with 121 XM-1 tanks per brigade. We also assumed that, for sparing purposes, all the active XM-1s would be assigned to brigades.

In reality, factors such as: (1) the sizes of brigades, (2) the number of tanks deployed outside of brigades, and (3) the number of tanks supported by

each ASL, are still being determined. If the number of tanks varies significantly by ASL, or if there are more than 17 ASLs (one for each of the 17 brigades), then the cost of spares is likely to exceed our estimates. This is because our assumptions imply economies of scale (a lower investment for a specified level of availability) which may not be achieved if the assumptions are violated.

Our third peacetime assumption was made because DRAMA was designed to represent two echelons of supply. Modifications to represent another echelon would have been very time consuming. Therefore, the GS echelon and the depot echelon had to be treated as one.

The assumption of no lateral resupply applies to resupply across brigades. This assumption was necessary simply because we do not know how to reflect lateral resupply accurately in a spares optimization model. The assumption of no cannibalization was made because we believe that the reality of peacetime operations is more closely approximated by this assumption than by the assumption of complete consolidation of parts shortages. (We do not know how to model a policy of partial cannibalization.) Both of these assumptions tend to induce underestimation of tank availability but, at realistically high levels of availability, the error is probably small.

<u>WARTIME ASSUMPTIONS</u>

Modeling wartime availability of the XM-1 required four additional assumptions.

1. Only the parts designated as essential in Table I-4 can cause a tank to become unavailable.
2. There is no battle damage or attrition during the 30 days of war.
3. There is no resupply to the brigades, nor parts repair within the brigades, during the first 30 days of war.

4. All parts are stocked to their authorized limits at the start of the war.

Using the essentiality code in the TARCOM and ARRCOM provisioning data bases restricted the number of critical items in our data base to 29 (out of 70); with almost 15,000 items in the XM-1, it is likely that many more than 29 will cause the tank to be unavailable. Thus, this study's wartime analysis is highly optimistic.

The second assumption was made to isolate the effects of supply that attrition and combat damage would have obscured. Thus, wartime availability decay is likely to be higher than predicted by the modeling effort.

The assumption of no resupply is supported by the fact that wartime resupply, even if it were as fast as peacetime resupply, would have little effect on a brigade's ASL during the first 30 days of a war. A part with a 50-50 division of repair activity between general and depot support illustrates this fact. Depot resupply of this part, even with unlimited depot stock, would average 35 days: five days longer than the hypothetical war. (It should be noted that this assumption is based on peacetime operation.) Furthermore, spare parts may receive a lower transportation priority than personnel, ammunition, and other essential items, causing their resupply times to lengthen. Finally, the sharp increase in activity during a war (when tank utilization rates are expected to be dramatically greater than those in peacetime) is likely to cause repair and resupply delays.

Our assumption of initially full ASLs is based on the assumption that there will be sufficient time to stock up with war reserve spares prior to the initiation of hostilities and that ample war reserve spares will be accessible to every brigade. If such assumptions are true, it will be possible for an armored brigade's supply trucks to stock up to their authorized limits (which

are the prescribed stockage levels in the ASL). That is why we chose to use the optimal stock-level lists from DRAMA as the stockage posture at the start of the war.

DATA BASES AND SOURCES

Data at the system level were obtained primarily from the PM. In some instances, the logistics data obtained from the PM differed from the TARCOM and ARRCOM data. When this occurred, the TARCOM and ARRCOM estimates were used. The system-level data are shown in Table I-1.

Data at the component level, except for removal rates, were obtained from TARCOM and ARRCOM. After the initial data bases were constructed, increases in some component costs (due to inflation) were obtained from the PM.

When this study began only a fraction of the items on the XM-1 had been analyzed by TARCOM and ARRCOM. Thus, the data base was far from complete. In fact, the filtering out of low-cost items and those not having a traceable relationship to the major tank assemblies, reduced the data base to 70 items. The items remaining in the data base, although representing most of the repairable, high-cost, high-demand items (including the engine and transmission), are a small fraction of the number of parts in the tank (15,000). As a result, our cost estimates for XM-1 spares are probably lower, and the availability estimates higher, than can realistically be expected.

Credible component removal rates were not available at the time of this analysis; they had to be inferred from maintenance actions observed during OT-II. TARCOM, confronted with this paucity of empirical data, assigned removal rates of six per hundred-thousand miles to many of the 70 items. Of course, many items had no observed removals during OT-II. The data problem was compounded by the fact that Chrysler's data base contained unscheduled maintenance action rates (UMARs), not component removal rates. Component

removal rates were estimated with the assistance of staff members of the Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs, and Logistics).

TABLE I-1. SYSTEM-LEVEL DATA

VARIABLE NAME	VALUE
Expected Utilization Rate	1000 miles per year
Supply Availability Goal	96 per cent[1]
Component Repair Times:	
At Org	3 days
At DS	15 days
At GS	45 days
At Depot	150 days
Component Order-and-Shipping Times:	
DS to Org	0 days
GS to Org	10 days
Depot to Org	60 days
Condemnation Pipeline Time	540 days
Component Turnaround Time (at a site):	Repair time (at site) plus order-and-shipping time

The following assumptions and definitions were applied to develop component removal rates:

1. The Chrysler data base accurately reflects the percentage of subsystem unscheduled maintenance actions (UMAs) attributable to each component. The UMAR of subsystem i is denoted by U_i and the proportion of the actions attributable to component j in subsystem i is denoted by $P_{i,j}$.

2. The ratio of removals to UMAs is 1/2. This is assumed for all components at all reliability levels.

3. a) We define K_i as the ratio for subsystem i of the subsystem's OT-II UMAR to its Chrysler UMAR.

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[1]Based on a 92 per cent operational readiness threshold specified by DCP 117A, May 1978, it seems reasonable to assume that the availability with respect to spares must be at least 96 per cent.

b) There are three sets of "K-factors," one set for each of the postulated failure rates. The 145-MMBF K-factor is defined in (a) while the 240-MMBF and 320-MMBF K-factors were estimated by the PM or staff of the Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs, and Logistics) based on the assumption that the ratios of subsystem removals to subsystem failures remained the same.

Component removal rates were computed using UMARs for line-replaceable-units (LRUs) in the Chrysler data base and the previous assumptions, for each postulated level of tank reliability, by using the appropriate set of K-factors in the following expression:

$$(1/2)\ (P_{i,j})\ (U_i)\ (K_i).$$

The following series of tables helps clarify and quantify the preceding discussion. Table I-2 lists the subsystems and describes the match-ups between OT-II nomenclature and Chrysler's. Table I-3 shows the K-factors that were used for each of the data bases, and Table I-4 lists the names of the 70 items in our data base. Table I-5 presents the component-level data, including the component maintenance action rates.

TABLE I-2. MAPPING OF OT-II SUBSYSTEMS TO CHRYSLER SUBSYSTEMS

OT-II SUBSYSTEM	CHRYSLER SUBSYSTEM
A1 - MOBILITY/ELECTRICAL	151 154
A2 - SUSPENSION	131 132 133 134
A3 - TRACK	135 136
A4 - ENGINE	141
A5 - TRANSMISSION	142
A6 - FINAL DRIVE	143
A7 - MOBILITY/OTHER	12 144 145 155
B1 - FIRE CONTROL	171 172 175 177 179
B2 - GUN TURRET DRIVE & STABILIZATION	178
B3 - GUN MOUNT/RECOIL	161
B4 - GOVERNMENT FURNISHED EQUIPMENT	167 18
B5 - NON-MOBILITY ELECTRICAL	163 164 165 176
B6 - NON-MOBILITY OTHER	162 166

TABLE I-3. SUBSYSTEM K-FACTORS FOR POSTULATED TANK RELIABILITIES

SUBSYSTEM	K-FACTORS 145	240	320
A1	0.64	0.47	0.30
A2	0.33	0.33	0.33
A3	0.87	0.22	0.14
A4	6.92	4.60	2.97
A5	7.84	5.23	3.37
A6	16.15	10.76	6.94
A7	1.92	1.44	0.91
B1	0.78	0.56	0.56
B2	1.78	1.29	1.29
B3	a	a	a
B4	a	a	a
B5	0.06	0.06	0.06
B6	4.03	4.03	4.03

[a]Subsystems B3 and B4 contained no components from our 70-item data base, so their K-factors were irrelevant.

Because there were no OT-II removal rate data on some items (which had no recorded removals) and because many other items had no corresponding part number in the Chrysler data base, we decided to estimate removal rates from UMARs by assuming a constant ratio of one removal for every two UMAs. This particular ratio was selected because it resulted in a reasonable removal rate for the system as a whole (1300 removals per 100,000 miles, compared with a system failure rate of 1250 per 100,000 miles) and because it yielded a removal rate for the engine, the tank's most costly item, that was within five per cent of its documented removal rate during OT-II.

In retrospect, however, we believe that this ratio was too low, for it has come to our attention that the 145-MMBF reliability level inferred from the OT-II data base did not account for all the tank's failures and removals. For example, if a failure or removal was induced by human error, it was discounted and, if several parts were removed and replaced in the course of a single maintenance action, only one removal was officially counted. Thus, out

TABLE I-4. 70-ITEM DATA BASE COMPONENTS

1.	DRIVERS HATCH	36.	POWER CONTROL UNIT
2.	SHOCK ABSORBER	37.	HAND PUMP ASSEMBLY
3.	ROADWHEEL	38.	ACCUMULATOR, HYD
4.	HUB/ARM ASSY IL*	39.	MANUAL DRIVE
5.	HUB/ARM ASSY IR*	40.	SLIP RING HULL/TURR*
6.	HUB/ARM ASSY 3-6 L	41.	CANT UNIT ASSEMBLY
7.	HUB/ARM ASSY 3-6 R7	42.	TURRET NETWORKS BOX*
8.	SPROCKET*	43.	TURRET AMMO RACKS
9.	TRACK ASSY*	44.	IMAGE CONTROL UNIT
10.	LINK, LEFT*	45.	THRM RECEIVER UNIT
11.	LINK, RIGHT*	46.	ELEC UNIT ASSEMBLY
12.	TRANSMISSION ASSY*	47.	COMMANDERS GPS
13.	FINAL DRIVE ASSY*	48.	COMP ELEC UNIT
14.	FAN, MIXED FLOW	49.	GYRO ASSY, RATE
15.	COOLER ASSY, ENG*	50.	CMDRS WPN STA SIGHT
16.	CLUTCH COOLING TRANS*	51.	CROSSWIND SENSOR
17.	COOLER ASSY, TRANS*	52.	GUNNERS AUX SIGHT
18.	COOLER ASSY, TRANS*	53.	LOS ELECTRONIC ASSY
19.	ALTERNATOR*	54.	COMP CONT PANEL
20.	VOLTAGE REGULATOR*	55.	ELEVATING MECH ASSY
21.	STARTER*	56.	ELECTRONIC UNIT
22.	HULL NETWORK BOX*	57.	COMMANDERS CONTROL
23.	HULL POWER*	58.	MOTOR, HYDRAULIC
24.	FIRE EXT CONTROL	59.	SERVOMECH ASSY, TRAV
25.	VALVE AND BOTTLE	60.	SERVOMECH ASSY, EL
26.	HEATER ASSY	61.	ENGINE ASSY, AGT1500*
27.	DRIVERS MASTER PANEL	62.	MODULE, FWD ENGINE*
28.	DRIVERS SEAT	63.	FUEL NOZZ ASSY COMB*
29.	DRIVERS INSTRUMENT PANEL	64.	LINER ASSY, CMBSTR
30.	PUMP, FUEL ELEC	65.	MODULE, REAR ENGINE*
31.	PUMP, FUEL INLINES	66.	ACCESS GRBX MODULE*
32.	DOME LIGHT ASSEMBLY	67.	OIL PMP & FIL ASSY*
33.	DRIVERS U. PERISCOPE	68.	ELMCH FUEL SYSTEM*
34.	BLOWER ASSEMBLY	69.	ELECTRONIC BOX*
35.	VALVE ASSEMBLY*	70.	OIL TANK ASSY*

*An essential component as designated by the essentiality code in the TARCOM and ARRCOM provisioning data bases.

TABLE I-5. COMPONENT LEVEL DATA

Component Number	Quantity per Tank	UMAs per 100,000 Miles	Cost $	Percentage of Repairs at Org	DS	GS	Depot	Percentage of Condemnations
1	1	9.75	1607	0	70	15	10	5
2	1	3.03	1435	0	20	30	40	10
3	14	88.47	227	0	0	0	80	20
4	1	9.37	1514	50	20	28	0	2
5	1	9.37	1514	50	20	28	0	2
6	4	4.87	2230	50	20	28	0	2
7	4	4.87	2230	50	20	28	0	2
8	2	8.60	318	50	20	28	0	2
9	2	50.00	8794	0	0	0	80	20
10	1	5.19	551	0	50	45	0	5
11	1	5.19	575	0	50	45	0	5
12	1	6.51	174135	0	0	0	95	5
13	2	.40	17363	0	0	75	20	5
14	1	.15	1759	0	70	15	10	5
15	1	1.34	788	0	45	50	0	5
16	1	1.50	793	0	40	45	0	15
17	1	1.34	663	0	45	50	0	5
18	1	1.34	636	0	45	50	0	5
19	1	1.69	5247	0	70	15	10	5
20	1	2.58	892	0	40	50	0	10
21	1	2.22	342	0	40	40	0	10
22	1	14.44	14331	0	70	15	10	5
23	1	.67	2889	0	70	15	10	5
24	1	1.23	623	0	0	0	95	5
25	1	.52	1445	0	0	0	95	5
26	1	3.94	821	0	0	75	20	5
27	1	8.60	1983	0	70	15	10	5
28	1	.12	1347	0	70	15	10	5
29	1	27.36	4816	0	70	15	10	5
30	4	.30	494	0	0	75	20	5
31	1	3.87	521	0	0	0	95	5
32	1	3.72	617	0	70	15	10	5
33	1	1.23	326	20	50	20	0	10
34	1	.59	844	0	70	15	10	5
35	1	1.23	2610	10	65	15	5	5
36	1	.33	1872	0	90	5	0	5
37	1	2.68	633	0	70	15	10	5
38	1	7.38	536	0	70	15	10	5
39	1	.07	694	0	40	50	5	5
40	1	3.96	5602	0	0	50	40	10
41	1	2.97	775	0	0	85	10	5
42	1	22.08	7891	0	75	20	0	5
43	1	.18	7739	0	75	10	10	5
44	1	6.35	41004	0	70	15	10	5
45	1	13.50	133338	0	70	15	10	5
46	1	1.38	7300	0	70	15	10	5

TABLE I-5. COMPONENT LEVEL DATA (Continued)

Component Number	Quantity per Tank	UMAs per 100,000 Miles	Cost $	Percentage of Repairs at				Percentage of Condemnations
				Org	DS	GS	Depot	
47	1	2.06	3726	0	0	0	95	5
48	1	8.72	19605	0	0	0	95	5
49	3	.27	3295	0	0	0	95	5
50	1	2.40	4100	0	0	0	95	5
51	1	.69	6787	0	70	15	10	5
52	1	1.79	7300	0	0	0	95	5
53	1	1.00	10232	0	95	0	4	1
54	1	2.55	5814	0	70	15	10	5
55	1	7.38	5095	0	0	85	10	5
56	1	4.8	6003	0	80	10	5	5
57	1	1.24	984	0	70	15	10	5
58	1	1.38	2538	0	0	0	95	5
59	1	.79	6531	0	0	0	95	5
60	1	5.86	5261	0	0	0	95	5
61	1	22.20	415546	0	0	0	95	5
62	1	9.40	187000	0	0	0	95	5
63	1	.19	2192	65	10	10	10	5
64	1	.13	3221	0	0	0	95	5
65	1	6.40	206965	0	0	0	95	5
66	1	3.20	40471	0	0	0	95	5
67	1	.49	6149	0	0	0	95	5
68	1	3.20	13627	0	0	0	95	5
69	1	.95	11595	0	0	0	95	5
70	1	.06	2871	0	70	15	10	5

of 540 OT-II maintenance incidents, there were only 168 "system failures", and on the basis of our estimates, only 179 component removals.

While we made many assumptions in developing our data base, we believe that the sensitivity relationships illustrated in the next two chapters are useful. Although imprecise, they at least portray the essential character of the true relationships and suggest the regions in which the true costs and availabilities lie.

II. PEACETIME RELATIONSHIPS AMONG SPARES COST, AVAILABILITY, AND RELIABILITY

OBJECTIVE

The objective of this analysis was to understand better the peacetime relationships among spares costs, availability, and reliability so that we could gain insight into their implications for XM-1 supportability.

SENSITIVITY OF INITIAL SPARES COSTS TO AVAILABILITY

The DRAMA model produced spares-cost-versus-availability curves for each system configuration. These curves are presented in Figure II-1.

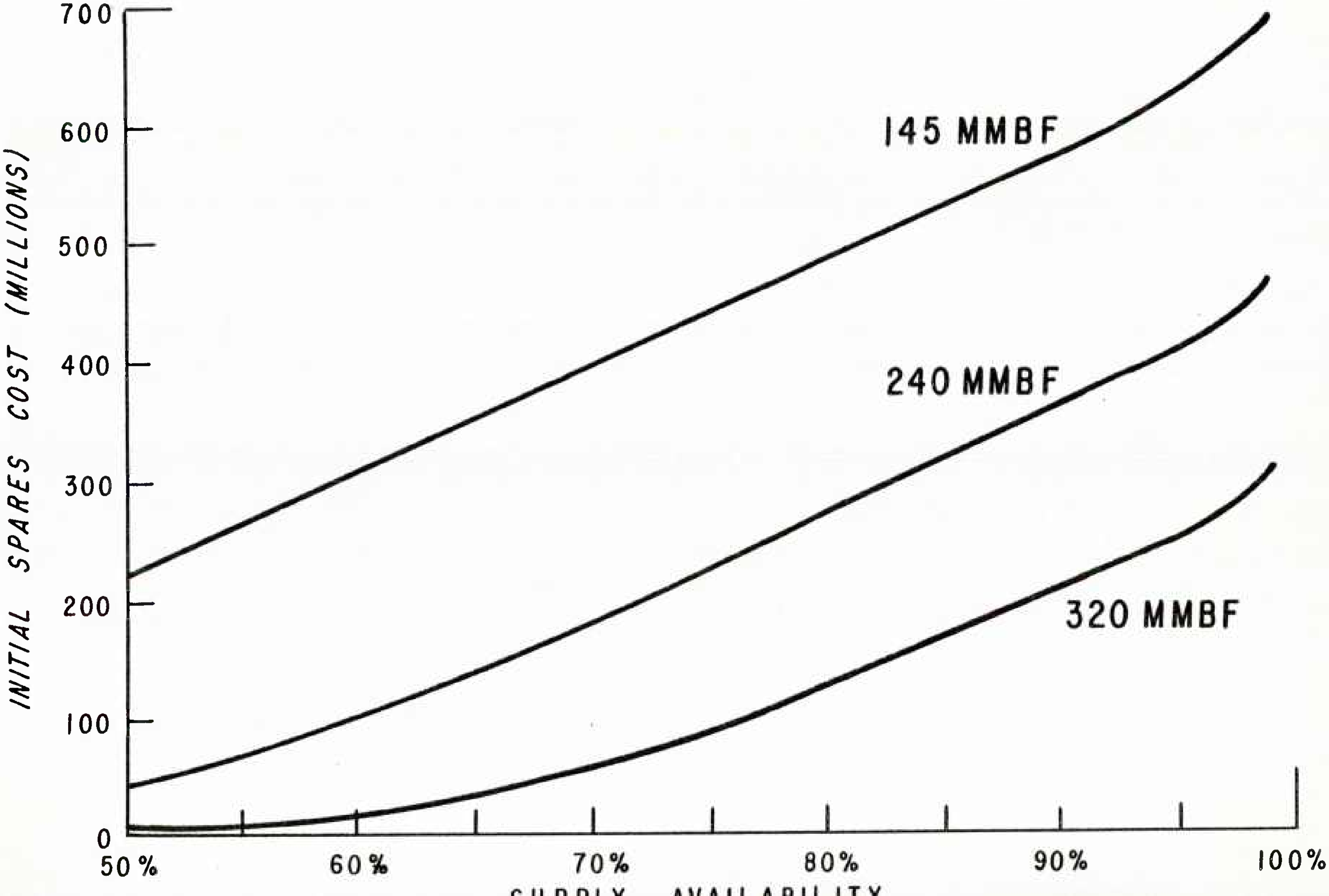
The cost-availability curve for the 320-MMBF configuration (Figure II-1) is typical of all of the curves in several key respects. It shows that the first spares purchased contribute more availability per dollar than the last. It also shows a near-linear relationship over a rather wide range of availabilities, a phenomenon that is explained in Appendix C. Finally, it shows that the XM-1 spares availability objective (96 per cent) is near the "knee" of the cost-availability curve, and is thus in a region where the cost of raising availability by one percentage point is over $40 million.

The 96 per cent availability objective for 2057 tanks requires an initial spares investment of at least $267 million with a 320-MMBF reliability level. This implies that the planned investment of $515.9 million reflected in the baseline cost estimate will support, roughly, 4000 active tanks, but only with spares of the 70 types contained in our data base. Thus, the entire planned investment would be consumed for these items alone, given the very favorable set of assumptions used in this study. With respect to the 70 items in our data base and approximately 4000 active tanks, an investment of $267 million would result in an estimated availability of:

(a) 96 per cent for the 320-MMBF configuration,

FIGURE II-1

SPARES COST vs AVAILABILITY



(b) 79 per cent for the 240-MMBF configuration, and

(c) 55 per cent for the 145-MMBF configuration.

SENSITIVITY OF COST AND AVAILABILITY TO RELIABILITY

Figure II-1 shows how the cost-availability curves shift with variations in tank reliability. Table II-1 contrasts the costs of the three XM-1 reliability levels at an availability level of 96 per cent.

TABLE II-1 SPARES COSTS

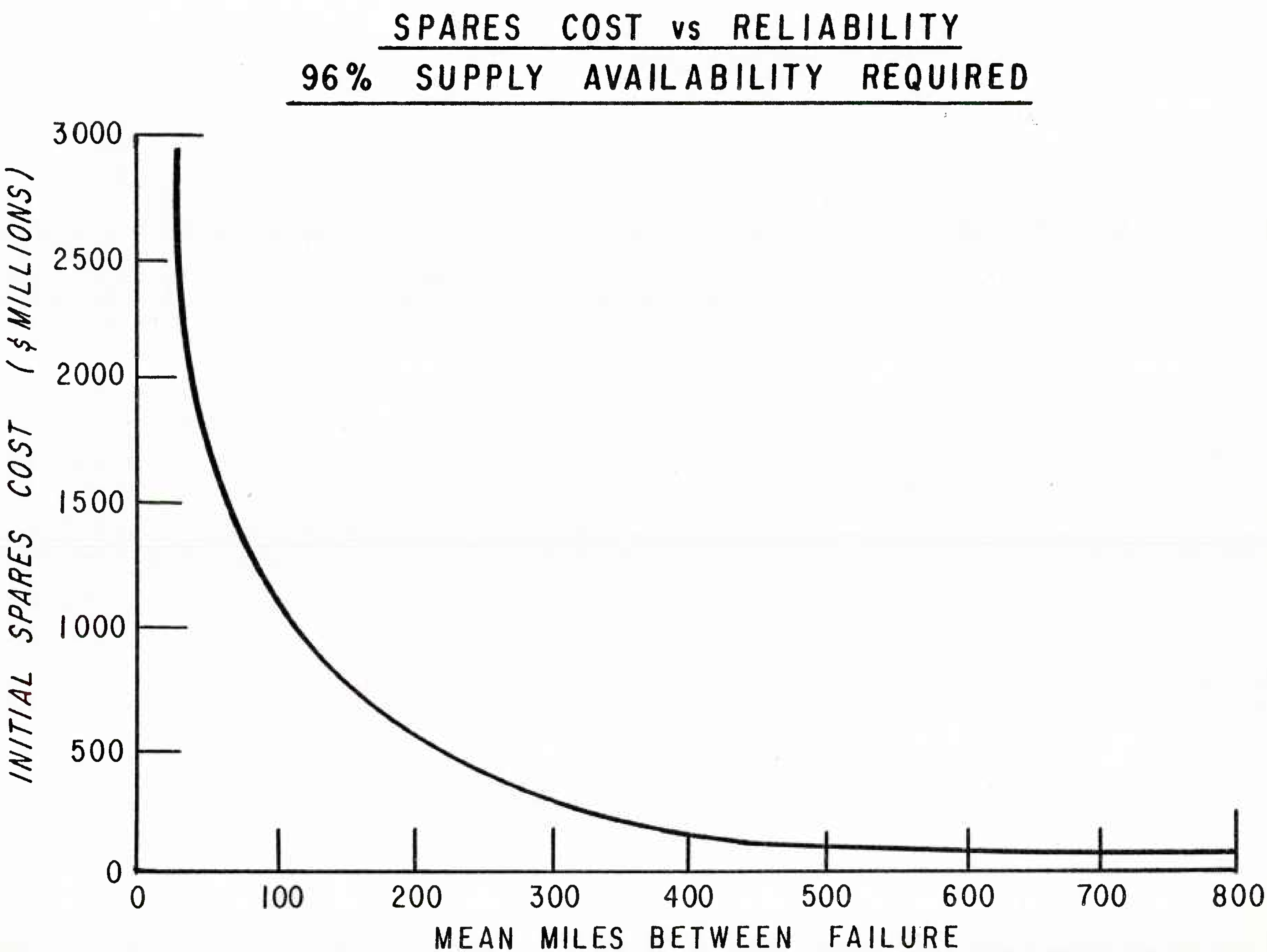
RELIABILITY	COST
145 MMBF	$636 million
240 MMBF	$419 million
320 MMBF	$267 million

These cost differences strongly suggest that substantial savings could be realized if the reliability of the XM-1 is improved. Moreover, because reliability improvement would reduce many cost elements besides spares (e.g., maintenance manpower costs), the overall savings could be much greater than the differences among our lower-bound estimates.

Another important fact about the XM-1's sensitivity to reliability is illustrated in Figure II-2, which represents the cost of achieving 96 per cent availability as a function of reliability. Although reliability growth has diminishing returns, there is dramatic cost-reduction potential in improving reliability to at least 320 MMBF.

Figure II-2 also shows that the reliability level observed in OT-II is near the knee of the cost-vs-reliability curve. Therefore, if the OT-II tests have been less stringent than actual operations, or if component wear-outs

FIGURE II-2



SPARES COST vs RELIABILITY
96% SUPPLY AVAILABILITY REQUIRED
INITIAL SPARES COST ($ MILLIONS)
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800
MEAN MILES BETWEEN FAILURE

reduce system reliability over time, the need for reliability improvement will be even greater than was suggested by the cost differentials in Table II-1.[1]

In Figure II-2, we assumed that all components experienced reliability improvements of identical percentages; thus, when tank reliability improved by a factor of K, every component's reliability improved by a factor of K. This uniform reliability improvement is inferior to the differential reliability improvement implicit in the 240- and 320-MMBF data bases (which applied different K-factors to each subsystem). This point is illustrated by noting that, at 96 per cent availability, the 240-MMBF data base generated a cost that was $20 million less than the 240-MMBF cost shown in Figure II-2. The reason for the superiority of our 240-MMBF data base is that reliability improvement in high-cost subsystems, such as the engine, is more beneficial than improvement in lower-cost subsystems, and that the 240-MMBF data base reflected better-than-average improvement in the high cost subsystems.

Reliability improvement programs appear to be most promising for the highest cost items. In particular, improvement of the engine, which accounted for more than 40 per cent of each configuration's spares costs, could lead to substantial savings.

WAR RESERVE SPARES

Our objective in buying war reserve stock was to begin hostilities with fully equipped tanks and ASLs. Thus, it was necessary to buy (at a minimum) a quantity of LRUs equal to the expected number missing from the European brigades.

---

[1]The reduction in MMBF over time has been well documented for the M-60. Four-thousand-mile (i.e., four-year-old) tanks have MMBFs approximately 70 per cent lower than new tanks. Parks College of St. Louis University, Reliability, Maintainability, and Cost Analysis of the M-60 A-2 Tank, U.S. Army Aviation Systems Command, St. Louis, Missouri, 1974.

The expected number of units missing from a brigade is equal to: (1) the expected number of units in repair in the brigade (i.e., organizational or DS-level repair), plus (2) the expected number of units in repair at, or in shipment to or from the GS, depot, or contractors (including processing and loading time), plus (3) the expected number of units condemned but not yet replaced.

At the availability goal of 96 per cent, the depot and GS levels would have virtually no backorders; therefore, the expected number of units missing would be approximately equal to the sum of the expected number of units in brigade-level repair and the expected number of serviceable units in shipment to the brigade. Using this approximation, we obtained the lower-bound war reserve cost for each reliability level with the following equation:

$$\sum_{i=1}^{NLRU} (FR_i)(NOB)\ \{\ (PD_i)(OSTD) + (PGS_i)(OSTGS) + (PDS_i)(DSRCT) + (PO_i)(ORCT)\ \}\ (Cost_i)$$

where i = the ith LRU,

NLRU = the total number of LRUs in the system,

FR_i = the frequency of removal of the ith LRU in a brigade,

NOB = number of brigades,

PD_i = the probability that a removed LRU is repaired at the depot,

OSTD = the order and shipping time from the depot,

PGS_i = the probability that the removed LRU is repaired at GS,

OSTGS = the order and ship time from GS,

PDS_i = the probability that a removed LRU is repaired at DS,

DSRCT = the DS repair cycle time,

PO_i = the probability that a removed LRU is repaired at the organizational level,

ORCT = the organizational repair cycle time,

and $COST_i$ = the cost of a spare unit of LRU_i.

Table II-2 shows the war reserve and total spares costs for each reliability level. War reserves require at least a 25 per cent increase in investment over and above the peacetime spares outlay. This is true for each of the postulated levels of reliability.

TABLE II-2. COMBINED PEACETIME AND WAR RESERVE COSTS
(In Millions)

SYSTEM MMBF:	145	240	320
WAR RESERVE COST	166	110	72
COMBINED COST	802	529	339
WAR RESERVE AS % OF PEACETIME SPARES	26	26	27

This level of war reserve sparing is conservative. It does not provide enough spares to sustain wartime levels of utilization, nor does it provide enough spares to maintain a high probability of having fully equipped brigades at the start of the war. A more realistic war reserve spares objective, say, 95 per cent confidence that a brigade would be fully equipped at the start of a war, or that a brigade could maintain 90 per cent availability over the first 10 days of wartime utilization, would be much more expensive.

III. WARTIME ANALYSIS

The purposes of our wartime analysis were: (1) to show the rough magnitude of wartime availability given the XM-1's current logistics plans, and (2) to show the sensitivity of wartime availability to utilization rate, reliability (MMBF), and opportunities for cannibalization.

METHODOLOGY

The cannibalizing model, CANNIB, and the non-cannibalizing model, NOCAN, were run for 30 days of war for an average XM-1 brigade with its complement of ASL and war reserve spares. The utilization rates modeled in our analyses ranged from 10 miles per day (three times peacetime utilization) to 145 miles per day (45 times peacetime utilization), and the reliabilities ranged from 145 MMBF to 320 MMBF. The models proceeded in an iterative, four-step fashion. The steps are:

STEP 1: Operate all available tanks for one operational period of arbitrary length; then, compute the expected demand induced for each part by such operation.

STEP 2: At the end of the period, compute the expected cumulative demands for each part since the start of the war.

STEP 3: Compute the expected number of unavailable tanks as a function of the cumulative demand for parts and the brigade-level spares supplies.

STEP 4: Compute the expected number of available tanks (total tanks in the brigade minus the unavailable tanks). Then return to STEP 1 at the start of the next period.

Although their steps were identical, the two models differed significantly in two respects. First, CANNIB proceeded in periods of a day, while NOCAN proceeded in periods of five minutes. Second, CANNIB computed the number of unavailable tanks as a function of: (1) the number of tanks in the brigade, (2) the quantity of each part on a typical tank, (3) the cumulative demand, and (4) the brigade-level supplies. (See Appendix B for details.) NOCAN treated the number of unavailable tanks as a function of the cumulative demand for parts and the brigade-level supply. This model assumed that one tank was unavailable for every removed part that could not be replaced. Therefore, the number of unavailable tanks was equal to the sum of unsatisfied demands across all essential components.

Differences between the availability computations of the models were dictated by their approaches to cannibalization; differences between their time periods were imposed for reasons of modeling accuracy. As a general rule, the accuracy of these models increases as their time periods become shorter. This is illustrated in Figure III-1(a) and III-1(b).

Figure III-1 and those that follow represent availability decay caused by parts shortages. Overall availability decay would be greater than supply decay as a result of combat damage, attrition, and maintenance requirements. Supply decay might be lower than depicted here due to the decay caused by attrition and combat damage. Combat damage will affect availability in two ways: (1) by increasing demand, it will cause greater unavailability early, and (2) by decreasing the number of available tanks early, it will reduce utilization-induced demand over the long run.

FIGURE III-1(a)

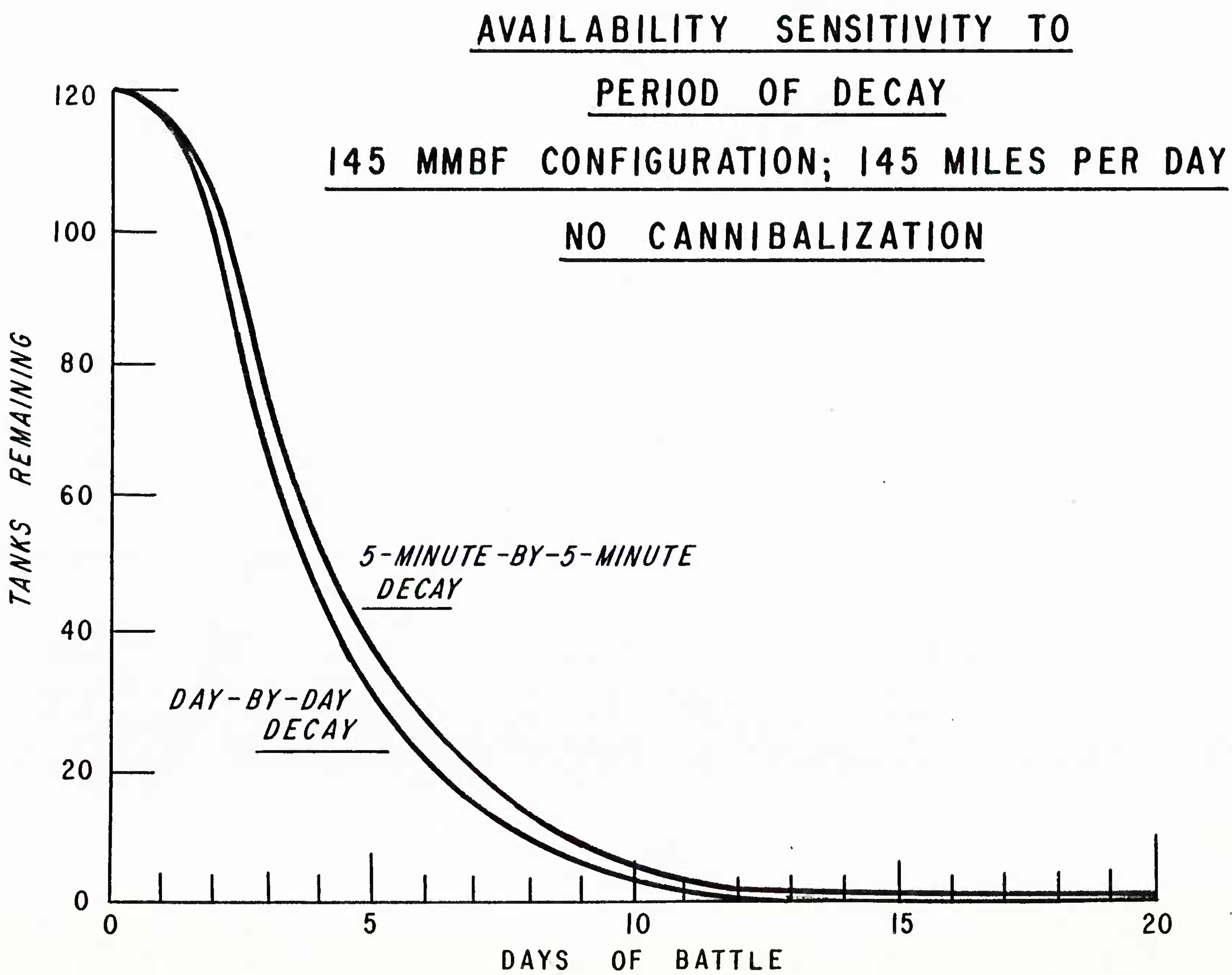
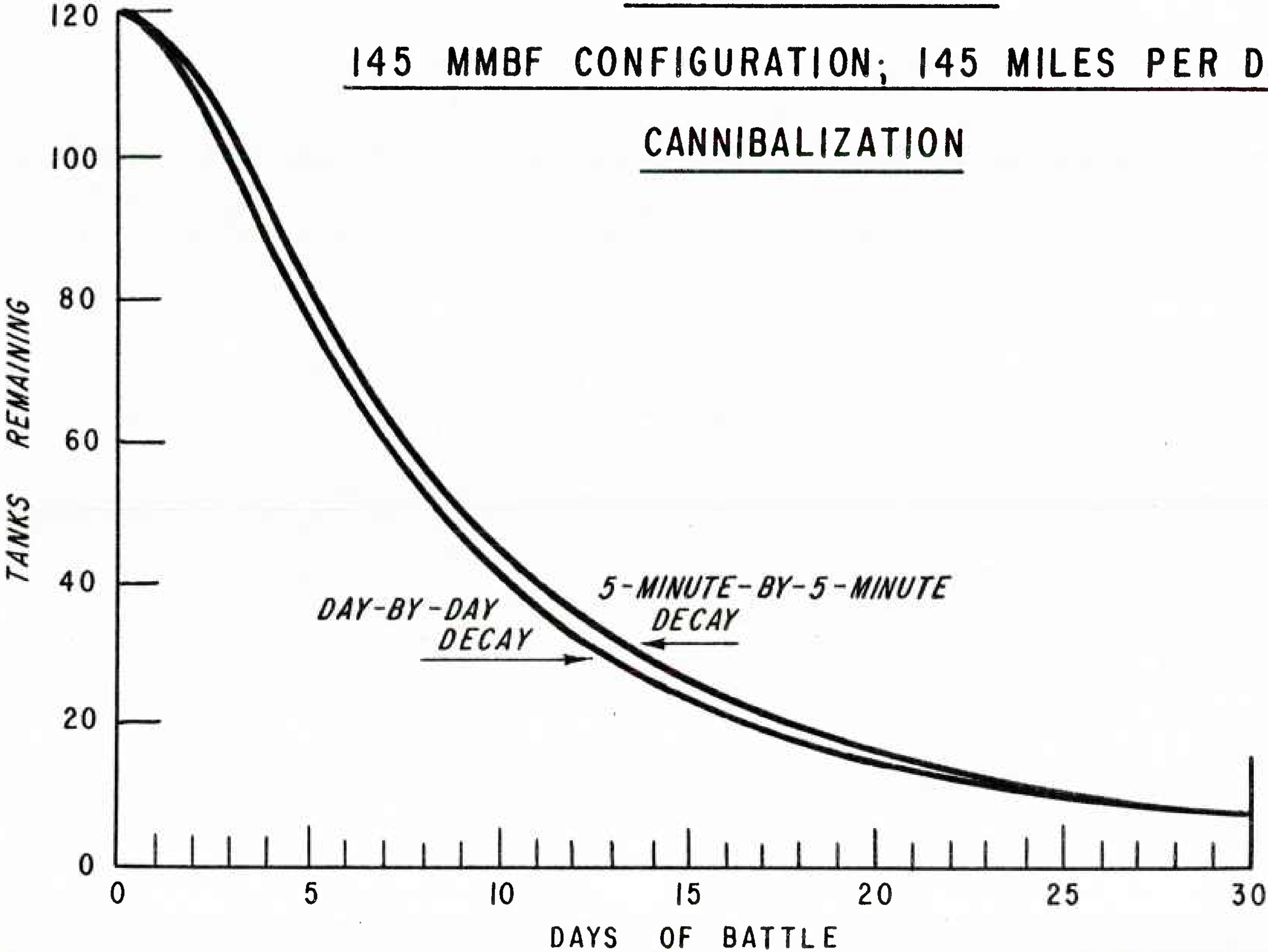


FIGURE III-1(b)

AVAILABILITY SENSITIVITY TO PERIOD OF DECAY

145 MMBF CONFIGURATION; 145 MILES PER DAY

CANNIBALIZATION



SENSITIVITY TO UTILIZATION RATE

We examined four different utilization rates: 10, 40, 100, and 145 miles per day (MPD). The lowest utilization rate was ten MPD, which could be considered a minimal wartime utilization. The next higher rate, 40 MPD, approximately equals the theater-wide average utilization postulated by the Army in their use of the Combat Evaluation Model (CEM) for U.S. brigades in the FY 1984 European Theater. The next higher rate, 100 MPD, equals the maximum daily average for a U. S. brigade in CEM's scenario. The highest rate, 145 MPD, approximately equals the rate forecast by the Training and Doctrine Command's (TRADOC) Armor School for an average day of intense combat. Although no brigade is likely to engage in intense combat for 30 consecutive days, protracted periods of intense combat are inevitable; the 145-MPD runs suggest what will happen to availability when they do occur.

Comparison of Figures III-2(a) and III-2(b) shows that the impact of high utilization rates is more pronounced in the non-cannibalizing scenario. The difference between the 30-day decay at 10 MPD and the 30-day decay at 40 MPD in the cannibalizing scenario amounted to approximately 40 tanks; the corresponding difference in the non-cannibalizing scenario is over 100 tanks. Thus, if a brigade cannot resort to cannibalization, its wartime availability is likely to be highly sensitive to the utilization rate (and, by implication, to other demand-driving variables).

SENSITIVITY TO RELIABILITY

Figures III-3(a) and III-3(b) illustrate the sensitivity of XM-1 availability to reliability. They show that the impact of cannibalization increases as reliability declines: (1) when the 320-MMBF configuration shifts from cannibalization to non-cannibalization, the expected number of available tanks on day 30 drops by 40 per cent, (2) when the 240-MMBF configuration

FIGURE III-2(a)

DECAY OF 240 MMBF CONFIGURATION AT VARIOUS UTILIZATION RATES CANNIBALIZATION

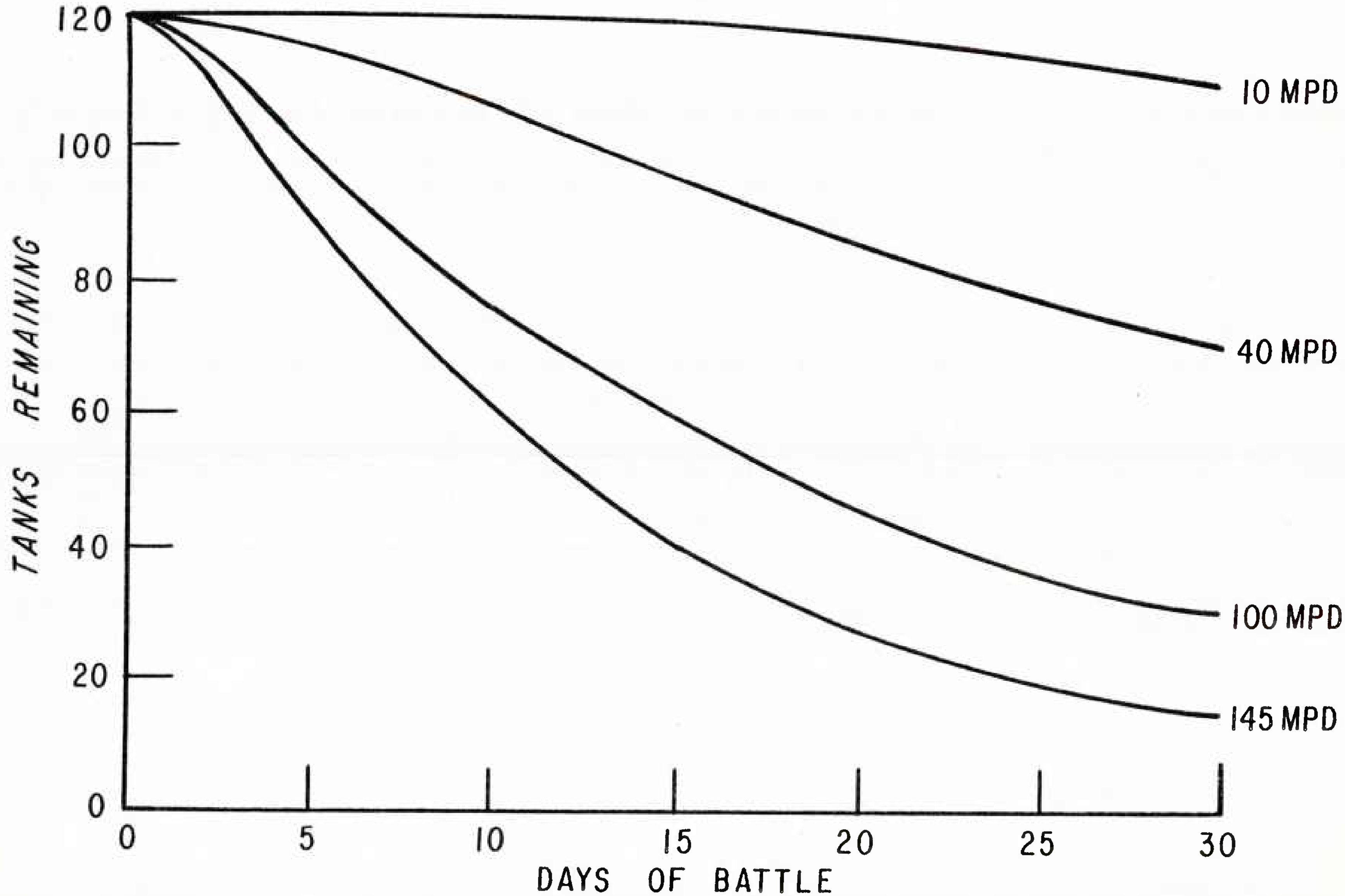


FIGURE III-2(b)

DECAY OF 240 MMBF CONFIGURATION AT VARIOUS UTILIZATION RATES NO CANNIBALIZATION

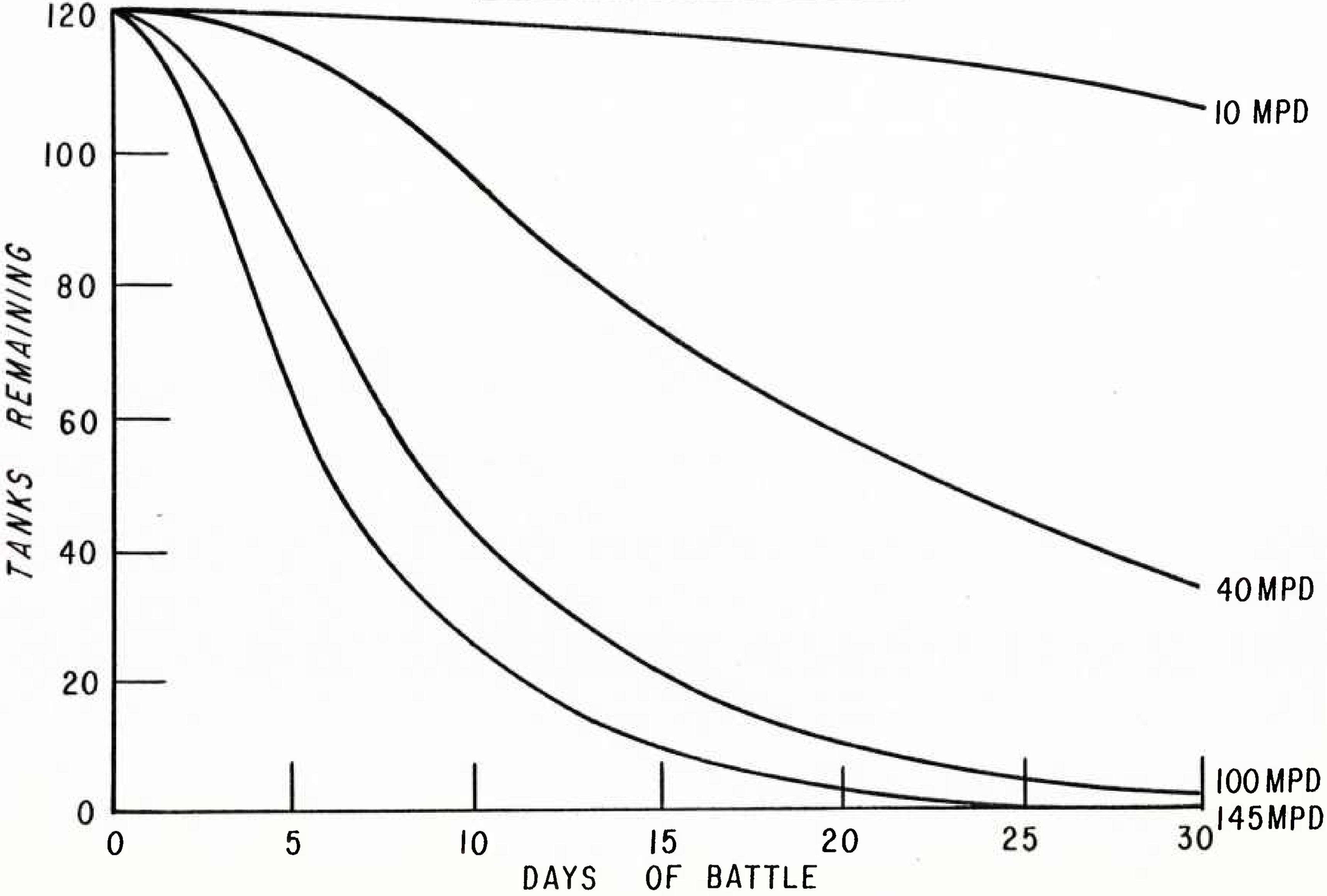


FIGURE III-3(a)

DECAY OF VARIOUS CONFIGURATIONS
AT 40 MILES PER DAY UTILIZATION
CANNIBALIZATION

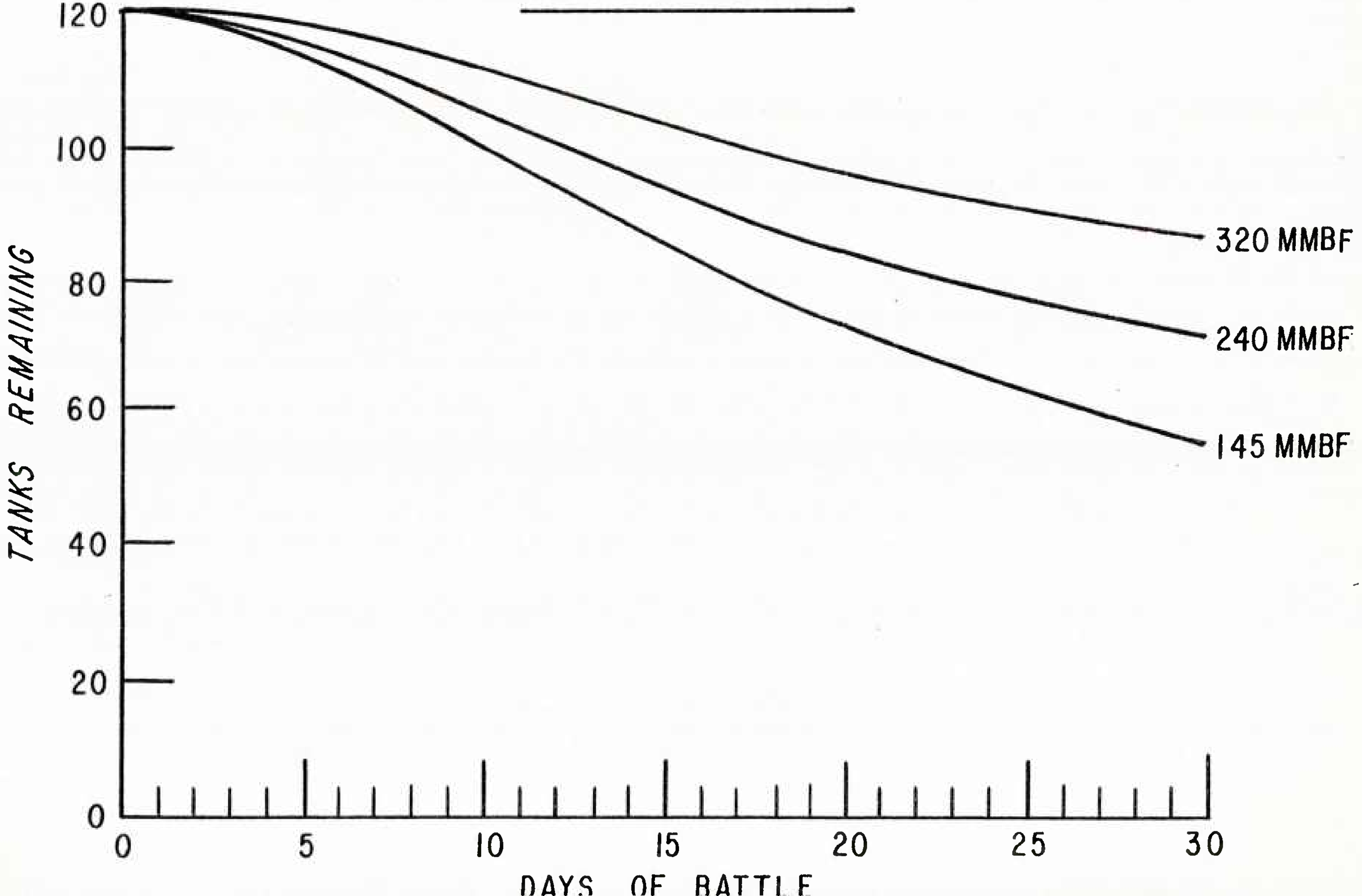
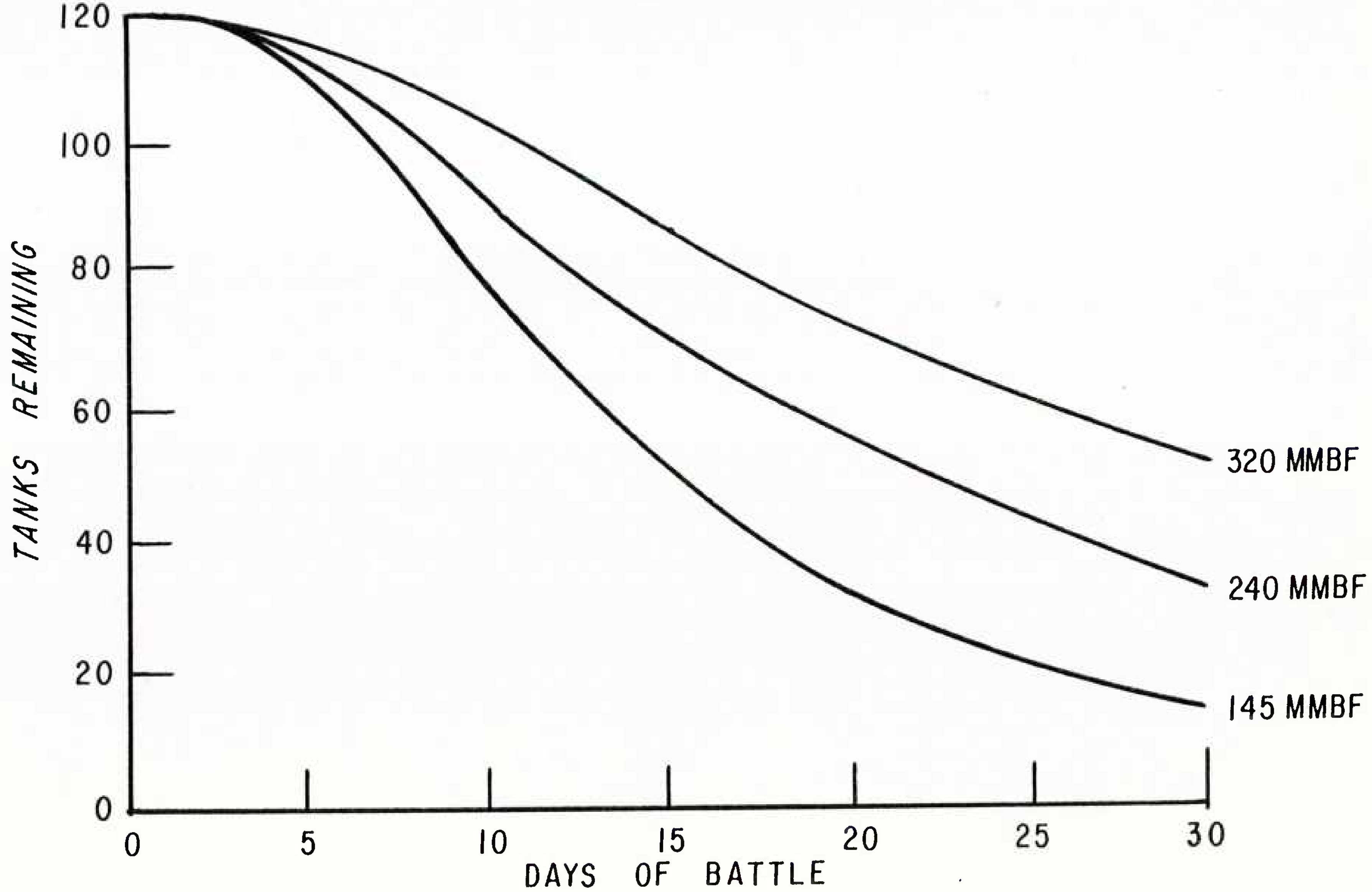


FIGURE III-3(b)

DECAY OF VARIOUS CONFIGURATIONS

AT 40 MILES PER DAY UTILIZATION

NO CANNIBALIZATION



shifts, the expected number of available tanks drops by 53 per cent, and (3) when the 145-MMBF configuration shifts, the expected number of available tanks drops by more than 75 per cent.

The number of XM-1 tank-miles achieved during a war (the area under an availability curve multiplied by the configuration's utilization rate) is sensitive to the system's reliability. Increasing reliability from 145-MMBF to 320-MMBF in the cannibalizing environment would increase total tank-miles from 101,000 to 125,000, or about 25 per cent. A similar reliability increase in the non-cannibalizing environment increases total tank-miles from 74,000 to 106,000, or about 44 per cent.

Total tank-miles are even more sensitive to reliability at higher utilization rates. For example, at 100 MPD in a non-cannibalizing scenario, reliability growth from 145 to 320 MMBF yields a 90 per cent increase in total tank-miles (79,000 to 150,000), while growth to only 240 MMBF yields an increase of 43 per cent (79,000 to 113,000).

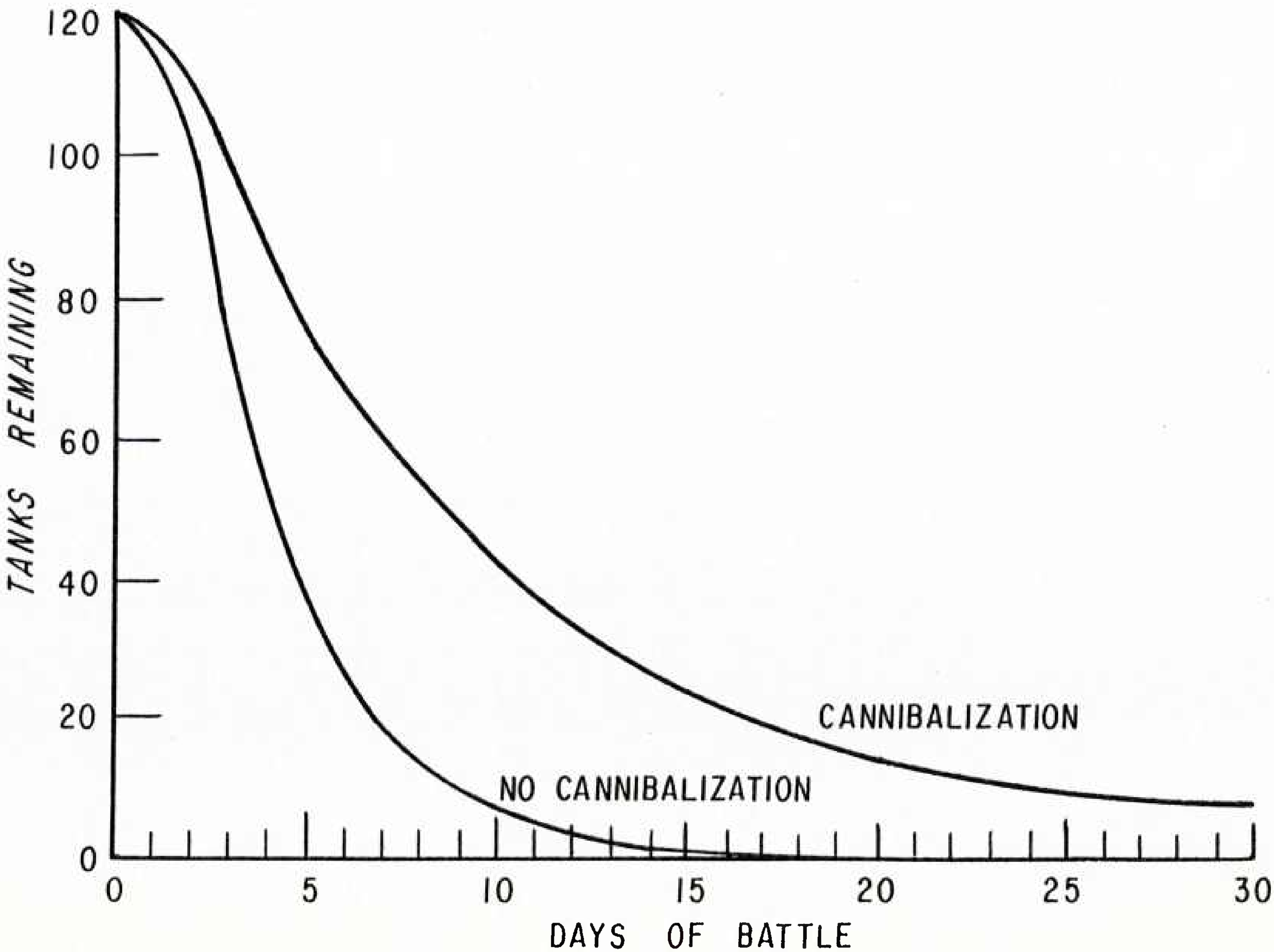
SENSITIVITY TO SCENARIO

Figure III-4 shows the comparative decay patterns of the 145-MMBF configuration for the cannibalizing and non-cannibalizing scenarios. Over the first five days of war, decay in the non-cannibalizing scenario is twice as fast (80 tanks lost to 40 tanks lost) as in the cannibalizing scenario, causing a lower level of total tank-miles. Total tank-miles after 30 days are 59 per cent less in the non-cannibalizing scenario (80,000 versus 174,000) than in the cannibalizing scenario. Similar relations hold for the other utilization rates; at 100 MPD, in the non-cannibalizing scenario, tank-miles are 37 per cent less and, at 40 MPD, they are 30 per cent less.

FIGURE III-4

DECAY OF 145 MMBF CONFIGURATION

145 MILES PER DAY UTILIZATION



SUMMARY OF WARTIME RESULTS

Our results show that wartime availability is extremely sensitive to reliability, utilization rate, and the extent of cannibalization. Sensitivity to cannibalization is particularly noteworthy, because it is highly dependent on the mode of operation. When forces are advancing, a larger percentage of immobilized tanks end up on the friendly side of the forward edge of the battle area (FEBA) where extensive cannibalization is feasible. However, when forces are holding steady or withdrawing, a smaller percentage of the immobilized tanks is likely to be on the friendly side of the FEBA, thus reducing the amount of cannibalization possible. Logistics planning for the XM-1 must therefore take account of its anticipated mode of operation.

The figures also indicate that, even in cannibalizing scenarios, availability decay appears to be disturbingly rapid. At 100 MPD, a 320-MMBF tank brigade would lose 25 per cent of its tanks for supply reasons in the first 10 days of war, a 240-MMBF brigade would lose 36 per cent, and a 145-MMBF brigade 50 per cent.

Clearly, it is desirable to reduce these rates of decay. Substantial reliability improvement appears to be the most promising method of reducing the decay rate; however, substantial stocks of war reserve spares and expeditious resupply of parts, as well as tanks in float, should also be considered as part of an overall program to achieve adequate wartime availability.

IV. CONCLUSIONS AND RECOMMENDATIONS

This analysis shows the essential character of the relationships among spares investment cost, utilization, reliability, and availability for the XM-1 tank system. We believe the evidence presented supports a compelling argument for reliability improvement programs for the XM-1.

The methodology used here demonstrates an approach to relating spares requirements to availability, reliability, and utilization; the approach depends on a spares optimization model that computes the least-cost mix of spares required for any specified level of weapon system availability. We found that the Army's provisioning data bases had not been sufficiently refined at the time of this analysis to be useful in estimating spares requirements; however, they did provide information on item essentiality. The manufacturer's work-breakdown structure and the Army's OT-II data base were the two primary sources of useful data on components. At the time of this analysis, just prior to DSARC III, initial provisioning attention was being given primarily to the long-lead-time items. These items constituted an especially attractive set of items for the analysis because they tend to have in common the characteristics of repairability, high cost, high removal rate, and mission criticality. They are also the items, by necessity, that receive the earliest provisioning attention; therefore, estimates of their characteristics tend to be more refined than those of other items. Clearly, the need exists to explore methods for dealing more effectively with the fact that, prior to DSARC III, item characteristics are not known on all the components of an end-item; in fact, data are incomplete and tentative even on the

long-lead-time items. One approach that seems useful is to compare the configuration of the system being examined with similar systems already operational, if such systems exist.

A fundamentally important feature of our approach is that it focuses on weapon system availability. We believe that availability as a measure of effectiveness is superior to other measures such as fill rate, operational rate, or expected backorders. The method is able to show what effects decisions about initial spares investments might have on weapon system availability and will suggest how to evaluate more reasonably the relative worth of various engineering changes to improve reliability. Furthermore, because of the optimization capability of the approach, one is able to determine the most prudent mix of spares investments to make, i.e., the least-cost mix, for any specified level of weapon system availability.

This work suggests the need for some enhancements to the basic methodology. One enhancement has to do with modeling the uncertainty about component demand rates and eventual prices paid for spares in the face of engineering changes that may cause some spares procured early in the life of the system to become obsolete or excess. Another enhancement in the form of spares procurement strategies that hedge against these kinds of uncertainties is needed to avoid procurement actions that result in eventual excesses. Both of these topics deserve further examination and development.

APPENDIX A

THE DRAMA MODEL

BACKGROUND

DRAMA is a mathematical model which maximizes a weapon system's availability for various levels of investment. Given certain weapon system characteristics, DRAMA computes optimal stock levels of LRUs at the depot and base echelons.[1]

DRAMA is an offspring of the LMI Availability Model, which is used by the Air Force for budget planning. It was originally developed to analyze the joint effects of avionics modularization and diagnostic error on spares costs. Today, DRAMA is used primarily to estimate the availability of new acquisitions, and to study the sensitivity of system availability to deployment patterns, component reliability, component levels-of-repair, and spares costs. DRAMA has not yet been fully validated, but it has been found to be consistent with the extensively validated LMI Availability Model.

The remainder of this appendix presents a short discussion of DRAMA's assumptions and an overview of its logic.

ANALYTICAL FRAMEWORK

The objective function of DRAMA is to minimize depot and base investment in spare LRUs subject to an availability constraint. In a single run, DRAMA solves this function for a number of availabilities, thus producing an optimal cost-versus-availability curve.

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[1]An LRU is a line-replaceable unit, i.e., a component that is removed from an end item, repaired, and reinstalled or replaced with a similar item. The 70 items in our data base are LRUs.

DRAMA's solution method is known as marginal analysis. The model creates inventories by making a series of spares purchases, each purchase being the one that yields the greatest marginal availability per dollar at that point in the purchasing sequence. It starts with no spares and builds up inventories by searching across all LRUs for the most cost-effective one. It "buys" an optimal quantity of that LRU and computes the benefit-to-cost ratio for its next purchase. DRAMA then searches across the components once again for the best purchase, and continues the process--search, buy, recompute a benefit-to-cost ratio--until a user-defined budget is exhausted, or until a user-defined availability goal is achieved. When finished with the optimization, DRAMA outputs the computed cost-availability relationship and generates files for future applications if requested.

KEY ASSUMPTIONS

DRAMA assumes a logistics system consisting of a central depot supporting a number of similar bases. For computational efficiency, all bases are assumed to be identical, equipped with the same number of systems operating at the same rates and receiving the same supply priority from the depot. Consistent with this "average base assumption," DRAMA allocates identical inventories of spares to each base.

The logistics system modeled in DRAMA functions as follows: whenever an LRU is removed from a system, the base replaces it with another LRU from its own inventory, if it has one. Then the base repairs the removed unit, if it can. If it can't, it ships the removed unit to the depot and simultaneously orders a replacement. When the depot receives the order, it ships the base a spare. However, if the item is out of stock, the base must wait until a procurement or repair activity provides the depot with a usable spare. Meanwhile, the depot tries to repair the removed unit. If the removed unit is

repairable, the depot completes the repair and adds the repaired unit to its stock. If the unit is not repairable, the depot condemns it and orders a replenishment spare from the unit's manufacturer. Replenishment keeps the population of spare parts constant and prevents the supply system from degrading its performance through component attrition.

DRAMA assumes that a base's spares demands are satisfied by its own spares or by resupply from the depot. No lateral resupply among the bases is allowed, and no cannibalization is modeled. In the future, a subroutine will be added to DRAMA to compute availability in a scenario of cannibalization, but, for the present, cannibalization is ignored.

DRAMA assumes that all LRUs are critical, and that if any one of them is unavailable, the system is down. It also assumes that component failures are independent so, given that a system consists of n components, its availability is equal to the probability that component one is available, times the probability that component two is available, . . ., times the probability that component n is available. "Availability," at both the component and system level, means availability with respect to supply: the probability that a system--or a part--is not down for want of spares. Unavailability as a consequence of maintenance delays other than for parts repair is not accounted for in the model; thus, the user must account for such delays if he wants the model to optimize for a target operationally ready rate.

Component failures are assumed to be Poisson-distributed with known means. Users who are uncertain about the mean rates of failure that they input should perform sensitivity analyses to demonstrate the impact of variability in the mean failure rate.

Finally, DRAMA assumes that only one weapon system is involved in any given optimization.

THE RELATIONSHIP BETWEEN THE EXPECTED NUMBER OF MISSING UNITS AND SPARES INVENTORIES

Assume initially that there are no spares at any echelon. Then answer the question: How many units of LRU_i are missing from the weapon systems at each base?

This question is not as easy to answer as it appears to be, for the number of missing units of an LRU is not constant. Units are not removed at a constant rate, and are not replaced in a fixed amount of time; thus, the number of missing units changes over time. Therefore, a more sensible question would be: How many units of an LRU will be missing, on the average, if there are no spares in the inventory?

The modified question is easy to answer. The average number of missing units is equal to the average rate of unit removal times the average waiting time for unit replacement. For example, if an LRU suffers 10 removals per day at each base, and if it takes each base, on the average, 15 days to obtain replacements, then its average number of missing units is 150. A useful way to express the average number of missing units is: the probability that one unit is missing times one, plus the probability that two units are missing times two, etc. In this appendix, the average number of units missing from each base will be referred to as EMU, which stands for the expected number of missing units.

One way of reducing EMU is to give spares to each base. Giving just one spare to each base will reduce the number of missing units to zero when it otherwise would have been one, to one when it otherwise would have been two, and to N-1 when it otherwise would have been N. The expected number of missing units will therefore be reduced from

$$\sum_{i=1}^{n} Pr(i) \times i$$

to

$$\sum_{i=2}^{n} Pr(i) \times (i-1),$$

for a net reduction of

$$\sum_{i=1}^{n} Pr(i),$$

where Pr(i) is the probability that i units are missing given zero spares and n is the number of units installed.

Giving two spares to each base has a similar, but larger impact on EMU. The number of missing units will be zero when it otherwise would have been two, one when it otherwise would have been three, and N-2 when it otherwise would have been N. Therefore, the expected number of missing units will be reduced to

$$\sum_{i=3}^{n} Pr(i) \times (i-2),$$

for a gross reduction of

$$\sum_{i=1}^{n} Pr(i) + \sum_{i=2}^{n} Pr(i),$$

where the first sum is the net reduction attributable to the first spare and the second sum is the net reduction attributable to the second. Similar sums, strictly decreasing in magnitude, express the net reductions of the third, fourth, fifth, ..., and Nth spares at each base.

Another way to reduce EMU is to give spares to the depot. The more spares the depot has, the faster it can fill the bases' orders, and the shorter the average waiting time will be for replacement units. Since the expected number of missing units at the base is proportional to average waiting time, giving spares to the depot reduces the expected number of missing units at each base.

Since both depot and base spares can reduce EMU, there is a tradeoff between buying spares for the depot and buying spares for the bases. This tradeoff presents DRAMA with an allocation problem that it solves while optimizing investments across different types of LRUs.

THE RELATIONSHIP BETWEEN AVAILABILITY AND THE EXPECTED NUMBER OF MISSING UNITS

For a particular LRU, the fraction of parts missing from a base's systems is equal to

$$\frac{EMU}{(SPB)\ (QPS)},$$

where SPB is the number of systems per base, and QPS is the quantity of LRUs per system.

Therefore, the fraction of parts not missing is

$$1 - \frac{EMU}{(SPB)\ (QPS)}\ .$$

In DRAMA, an LRU's availability is defined to be the probability that the LRU is in place in all of its applications on a given system. For instance, an LRU that had 50 per cent of its units in place and had two applications per system, would have an availability of 0.5 times 0.5, or 25 per cent. This computation is based on the assumption that the shortages of the LRU are randomly distributed over all of its applications.

The mathematical expression of LRU availability is thus

$$\left[1 - \frac{EMU}{(SPB)\ (QPS)}\right]^{QPS}\ .$$

Because the LRUs are assumed to fail independently, the probability that they all are available on a single aircraft is equal to the product of their availabilities. System availability in DRAMA is therefore given by

$$\prod_{i=1}^{NLRU} \left[1 - \frac{EMU_i}{(SPB)\ (QPS_i)} \right]^{QPS_i} ,$$

where NLRU is the number of LRUs in the system,

EMU_i is the expected number of missing units of the ith LRU, and

QPS_i is the quantity-per-system of the ith LRU.

THE IMPACT OF ADDING COMPONENTS TO A DATA BASE

If we were to input a complete data base of XM-1 LRUs into DRAMA instead of our 70 selected items, our spares cost estimates for a particular availability level would increase for two reasons: (1) spares for the new LRUs would have to be purchased, and (2) additional spares of the 70 selected LRUs would have to be purchased.

The reason for the increase in the spares inventories of the 70 items is the impossibility of obtaining 100 per cent availability for the new items. No part can be spared to exactly 100 per cent availability, so the availability product of the new items is sure to be less than 100 per cent. Therefore, the total system availability, given these new items, will be equal to the 70-item availability times some number less than 100 per cent. If the 70 items have a collective availability of only 96 per cent (which is what their current spares inventories provide) then total system availability will be necessarily lower than 96 per cent. To get the system availability above 96 per cent, then, one must boost the 70-item availability by buying more spares.

APPENDIX B

THE CANNIBALIZATION LOGIC

CANNIBALIZATION SCENARIO

For the cannibalization scenario, we make the following assumptions:

a. At any specified point in time, the number of unavailable tanks is equal to the largest ratio of demands to applications-per-tank for any single part in the inventory.

b. The number of any given part in resupply at any time depends only on total tank utilization up to that time and not on the numbers of other parts in resupply at that time.[1]

These assumptions facilitate the computation of the probability distribution of unavailable tanks as well as their expected number.

The derivation of the mathematical model proceeds as follows.

Let W = a random variable: the number of unavailable tanks at some specified point in time.

The expected value of W is given by

$$E(W) = \sum_{w=o}^{N} w \cdot Pr\{W = w\},$$

where N denotes the number of tanks in the brigade.

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[1] Resupply is defined to include repair, at any level, retrograde shipment, and order-and-shipment to the using organization.

Note that $\Pr\{W = w\} = \Pr\{W \le w\} - \Pr\{W \le w-1\}$.

Thus,

$$E(W) = \sum_{w=o}^{N} [w \cdot \Pr\{W \le w\} - w \cdot \Pr\{W \le w-1\}]$$

$$= \Pr\{W \le 1\} - \Pr\{W \le 0\} + 2\Pr\{W \le 2\} - 2\Pr\{W \le 1\}$$

$$+ 3\Pr\{W \le 3\} - 3\Pr\{W \le 2\} + \ldots + N\Pr\{W \le N\} - N\Pr\{W \le N-1\}.$$

But $\Pr\{W \le N\} = 1$; therefore,

$$E(W) = N - \sum_{w=o}^{N-1} \Pr\{W \le w\}.$$

Now, let A denote a random variable: the number of available tanks.

Then, $A = N - W$, and

$$E(A) = E(N-W) = N-E(W) = \sum_{w=o}^{N-1} \Pr\{W \le w\}.$$

By our original assumptions,

$$\Pr\{W \le w\} = \Pr\{\text{no part has more than } wq_i \text{ unsatisfied demands}\}$$

$$= \prod_{i=1}^{k} p\,(X_i \le s_i + wq_i;\ §_i),$$

where X_i = the number of parts of type i in resupply,

s_i = the stock level of part i,

q_i = the quantity per tank of part i,

$§_i$ = the expected number of demands for part i in some specified period of time ($§_i$ is a parameter of probability distribution of X_i),

and k = the number of line items in the inventory.

Finally,

$$E(A) = \sum_{w=o}^{N-1} \prod_{i=1}^{k} p\,(X_i \le s_i + wq_i;\ §_i).$$

NON-CANNIBALIZATION SCENARIO

For a scenario in which cannibalization is not permissible, availability is computed according to the formula

$$\text{AVAILABILITY} = \frac{\text{E (AVAILABLE)}}{N} = \frac{N - \sum_{i=1}^{k} UD_i}{N},$$

where UD_i is the expected number of demands for part i that have gone unsatisfied.

Therefore, for each unsatisfied spares demand there is one tank down.

APPENDIX C

DETAILS OF THE XM-1 SPARES COST-AVAILABILITY RELATIONSHIP

The cost-availability relationships in this report are not typical of those we have seen on other weapon systems. We will discuss the 320-MMBF relationship in this Appendix. It is unusual in three respects:

a. The availability rate reaches about 50 per cent with a spares investment that is unusually small relative to the tank's acquisition cost.

b. The DRAMA model computes a sequence of spares purchases across the lower ranges of availability rate that exhibits <u>increasing</u> marginal returns of availability per unit cost.

c. The relationship is nearly linear over a remarkably wide range of availability rates.

Each of these apparent anomalies is induced by the characteristics of the data base. The fact that about 50 per cent availability is reached with a relatively modest investment is due to the characteristics of a single item, the roadwheel. The roadwheel has the largest expected number in resupply and the lowest cost of all the items in the data base; therefore, purchases of roadwheels yield high returns in availability for relatively little cost. Another factor that contributes to this cost-availability behavior is that there are only 70 items in the data base; therefore, the availability is about eight per cent before the first spare is purchased.

The counterintuitive nature of increasing marginal returns over the range of availabilities below about 35 per cent is also attributable to the roadwheel. Besides having a very large expected number in resupply (EMU) and a low unit cost, the roadwheel has a high quantity per system (QPS), viz., 14

installed on each tank. Table C-1 illustrates the increasing marginal return effect.

TABLE C-1. XM-1 COST AVAILABILITY

Total Roadwheels Purchased	Incremental Purchases	Number at Depot	Number at Each Brigade	EMU (Each Brigade)	Total Cost	System Availability
1	-	1	0	189.9	227	.085
325	324	325	0	170.9	73775	.100
1086	761	1086	0	126.1	246522	.150
1639	553	1639	0	93.6	372053	.200
2076	437	2076	0	67.9	471252	.250
2438	362	2370	4	46.6	553426	.300
2748	310	2425	19	28.3	623796	.350

The characteristic of increasing marginal worth of roadwheels is clear from these data. An increase of five per cent availability from 10 to 15 per cent, for example, requires the purchase of 761 roadwheels, while a five per cent increase from 30 to 35 per cent requires only 310.

DRAMA makes the assumption that shortages are randomly distributed across all installed positions. Because of the roadwheel's large EMU and high QPS, many tanks are short more than one roadwheel when there are few spares; therefore, the shortages relieved by early purchases tend to make fewer tanks available simply because a higher proportion of the holes they fill are on the tanks with other holes. Note that this is an idiosyncracy of the model; clearly, real-world behavior would not seem so irrational. Fortunately, this effect of increasing marginal worth is apparent only at unrealistically low spares levels and is not a serious practical problem.

The nearly linear character of the cost-availability relationship between about 80 and 95 per cent is attributable, again, to a single item: in this case the turbine engine. Each engine purchased in that availability range reduces the EMU of the engine by almost one unit. Since the QPS is one per tank, the result of the purchases is essentially a constant marginal return per dollar invested.